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**REFLECTIVITY MEASUREMENTS WITH 10.6
MICROMETER INFRARED RADIATION**



TECHNICAL REPORT

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and

J. W. McGarvey

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A reflectivity measurement technique utilizing chopped 10.6 micrometer infrared radiation from a CO₂ laser was developed under In-House Laboratory Independent Research Funding in the Research Directorate, Weapons Laboratory at Rock Island. The reflectivity of various target and environmental surfaces was determined with this technique. This technique was also used to determine the emissivity of a manganese-phosphate-coated barrel section; the results compared well with data obtained by more conventional methods.

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OBJECTIVE

The objective of this project was to determine the feasibility of obtaining the emissivities of Army materials from reflectivity measurements and to determine the reflectivities of target and environmental surfaces at 10.6 micrometers (μm) with pulsed CO_2 laser radiation

INTRODUCTION

High-speed infrared instrumentation techniques for temperature mapping the components of high-performance weapons have been developed in the Research Directorate, Weapons Laboratory at Rock Island, and previously reported. As with other infrared techniques for temperature measurement, the emissivity of the surface of the material under investigation must be known over a broad temperature range. This parameter can be determined by the measurement of the ratio of the infrared power radiated or absorbed by an object to the infrared power radiated or absorbed by a source of known emissivity. In practice, this usually means the comparison of the power radiated by a black-body at the same temperature

For previous studies, in determining gun barrel emissivities, a hole was bored in the side of the barrel to enable a radiometer to be focused into the interior of the barrel. The barrel was heated by a current passing through a wrapping of nickel-chromium wire thermally and electrically insulated by sheet asbestos.² The radiation emerging from the hole in the barrel constituted a good approximation to black-body radiation that could be readily compared with the radiation emitted from the surface of the barrel. Thermocouples were used to monitor the temperatures at the surface and in the interior of the barrel. This method, however, is time-consuming and requires the destruction of the barrel.

Therefore, a faster, nondestructive method is desirable. In this report, results are described involving an investigation of the feasibility for determining the emissivities of various materials from their reflectivities by chopped 10.6 micrometer laser radiation. This method will be particularly useful for weapon component temperature-mapping investigations. In addition, reflectivity measurements of target and environmental materials are required for cannon-launched guided projectile (CLGP) investigations involving the use of an in-house developed bifunctional seeker and a 10.6 micrometer laser designator.

THEORY

Conservation of energy requires that incident power falling on a body must equal the sum of the amount of power

absorbed plus the amount reflected:

$$P_i = P_r + P_a \quad (1)$$

Dividing both sides by P_i and defining $a = P_a/P_i$ as the absorptivity or fraction of incident power absorbed and $r = P_r/P_i$ as the reflectivity or fraction of the incident power reflected, one obtains

$$1 = a + r \quad (2)$$

At thermal equilibrium, the emissivity equals the absorptivity and is written

$$\epsilon = 1 - r \quad (3)$$

Furthermore, the second law of thermodynamics implies that this relationship is true spectrally. Thus,

$$\epsilon(\lambda) = 1 - r(\lambda) \quad (4)$$

This expression indicates that the reflectivity should be measured at various wavelengths to obtain $\epsilon(\lambda)$.³ If the emissivity is a slowly varying function of wavelength, measurements at several wavelengths may be sufficient to specify the emissivity to sufficient accuracy to satisfy practical requirements for temperature mapping.

Using Wein's displacement law

$$T_{\lambda_{\max}} = b = 2897.8 \mu\text{m}^\circ\text{K} \quad (5)$$

one finds that a temperature of 500°K corresponds to $\lambda_{\max} = 5.8$ micrometers and 1200°K corresponds to 2.4 micrometers. Thus, reflectivities in the visible spectrum cannot be expected to be precise indicators of the emissivity in the 500°K to 1200°K temperature range.

Unfortunately, lasers radiating in the 2.4 to 5.8 micrometer range are not readily available. Therefore, a carbon dioxide laser radiating at 10.6 micrometers was utilized. Although this corresponds to only 273°K, this wavelength should provide useful information provided that the emissivity is not a rapidly varying function of wavelength.

INSTRUMENTATION AND PROCEDURE

In the investigations reported herein, the emissivity of an object was derived from an experimental measurement of the reflectivity of that object at 10.6 micrometers. To perform the measurements required, the samples were prepared and placed in the path of the laser beam on a plate mounted at an angle of 45° with respect to the optical axis of the laser. The radiometer that was used to measure the amount of reflected radiation was mounted on a goniometer and focused at the center of the area being illuminated by the laser. The goniometer enabled the radiometer to be moved through an angular range of 0 to 180 degrees with respect to the optical axis of the laser while the radiometer remained focused on the same spot.

The in-house constructed CO₂ laser has two collinear sections made of Pyrex tubing to contain the lasing gas. Each section is 33 inches long with an inside diameter of 0.875 inch and an outside diameter of 1 inch. This tube is surrounded by Plexiglas tubing, 20 inches long with an inside diameter of 1.75 inches to provide a water jacket. Water is circulated between the two tubes to cool the gas mixture flowing within the Pyrex and helps to stabilize the laser output characteristics. The two sections of the laser are joined with Quick Flange vacuum components. The mirrors, gas inlet, and vacuum port are connected to the ends of the tube in a similar manner. The laser tube assembly is mounted on an aluminum channel for rigidity. A schematic diagram of the laboratory-constructed laser is shown in Figure 1, and a photograph of the system is shown in Figure 2.

In this system, a flowing gas mixture of 5.2 torr of helium, 1 torr of carbon dioxide, and 1.5 torr of nitrogen is excited by the application of 6,500 volts, D C, to the center flange between the two tubes. Each end of the laser is grounded through a 65,000-ohm ballast resistor. During lasing, a potential of 3,500 volts is developed across each section while a current of 50 milliamperes is drawn. Germanium mirrors, one curved with a 4-meter radius of curvature and a reflectivity of approximately 100 per cent and the other flat with a

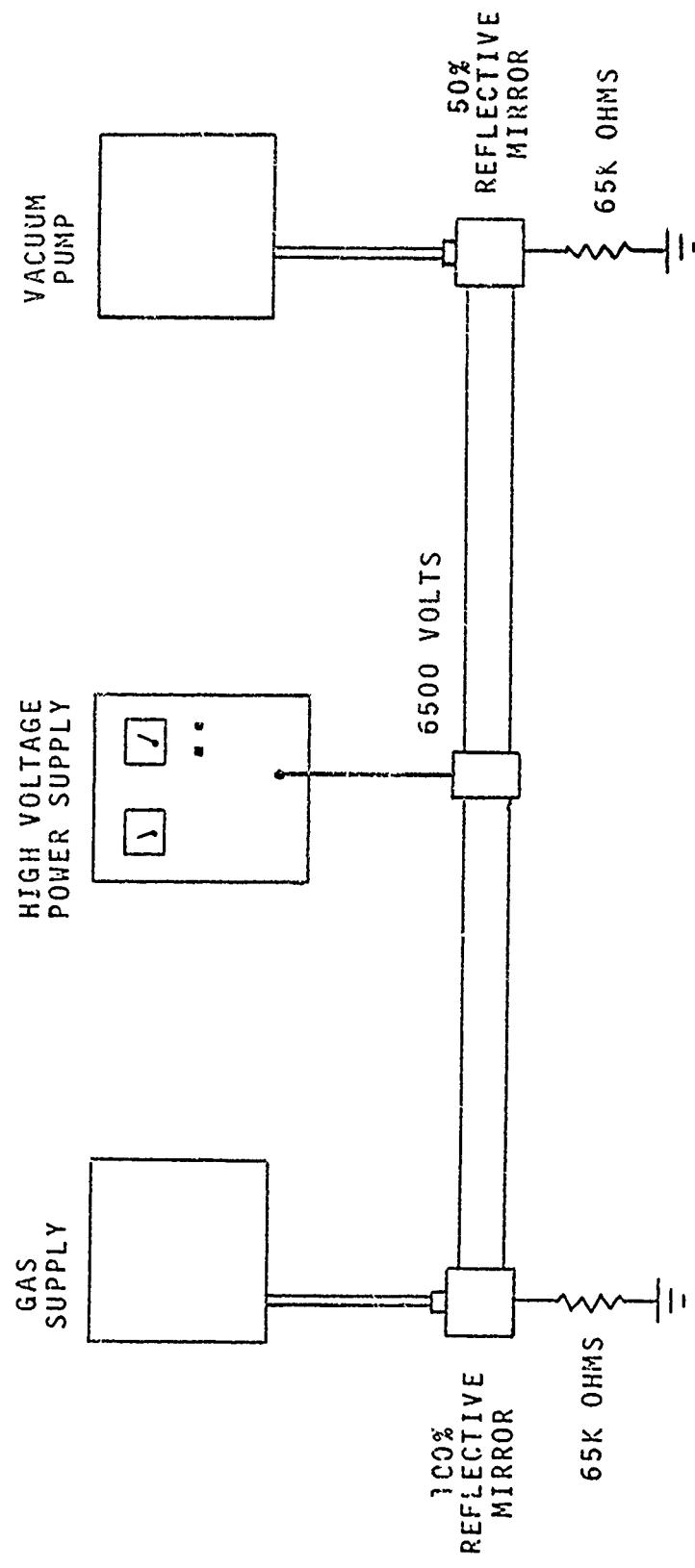


FIGURE 1
SCHEMATIC DIAGRAM OF LABORATORY-
CONSTRUCTED CO₂ LASER

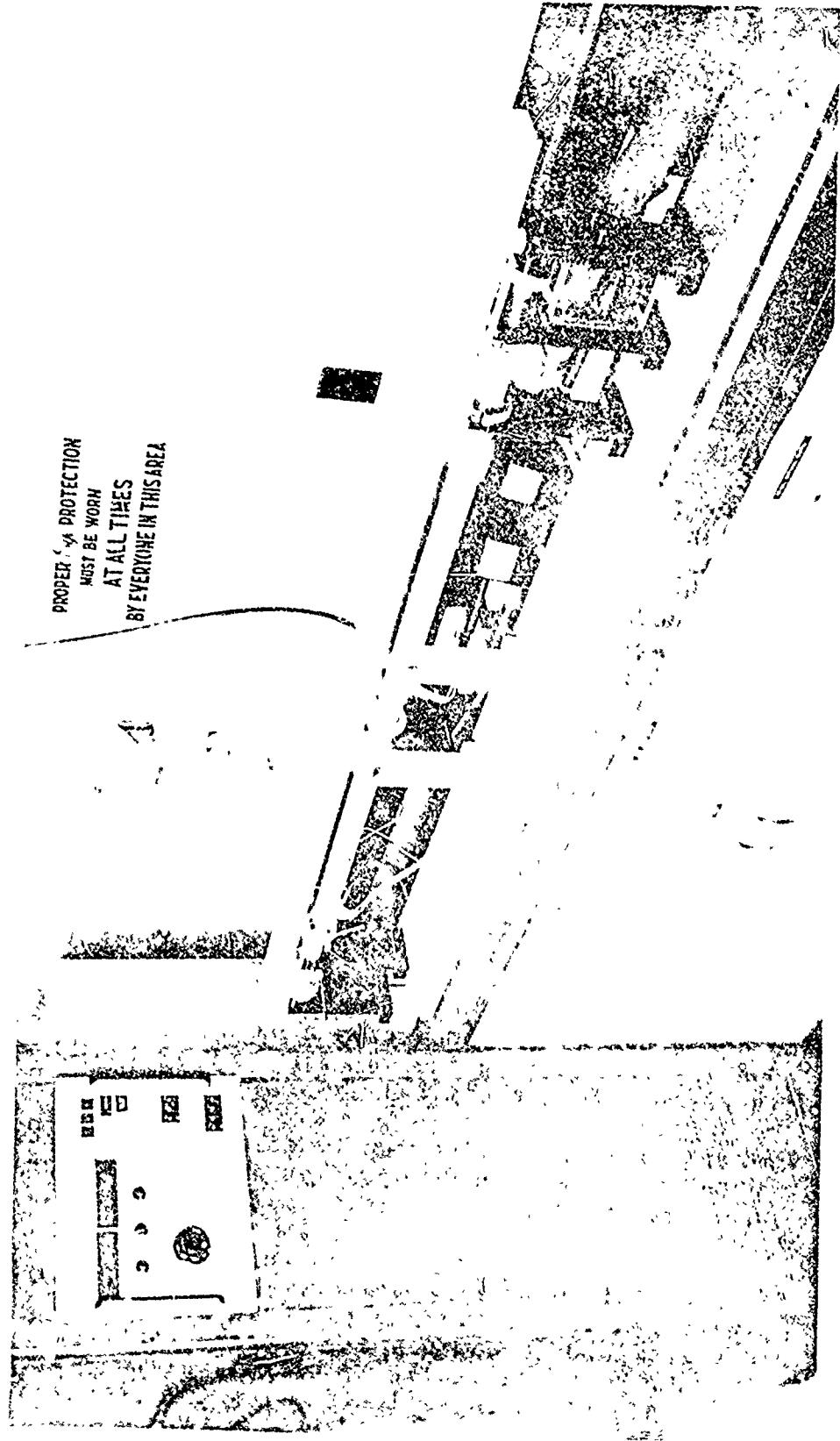


FIG. P 2

LABORATORY-CONSTRUCTED CO₂ LASER

reflectivity of 50 per cent, were used in the construction of this laser. In this configuration, the laser produced a maximum CW multimode output power of 35 watts.

A laboratory-constructed infrared telescope was used to expand the laser beam. The resulting shape of the beam incident on the sample was a distorted ellipse, the upper portion wider than the lower section, with a major axis of 1.4 inches and a minor axis of 1 inch. The beam was focused to a point and then allowed to expand to the desired size beyond this point. A reflective chopper was mounted at the focal point of the laser radiation at an angle of 45 degrees to the optical axis. The chopper served two purposes; (1) to allow continuous monitoring of the laser output and (2) to present an A.C. signal to the radiometer. The laser output was monitored by the positioning of a laser power meter 90 degrees to the optical axis so that, when the reflective chopper blade passed through the beam, the radiation was reflected onto the detector of the power meter. Since the laboratory-constructed radiometer was A.C. coupled and able to detect only changes in the signal, the chopping of either the incident or the reflected radiation was required. Errors due to sample heating, which was a slowly changing phenomenon, were minimized by placement of the chopper in the incident beam. Therefore, the radiometer detected only the reflected radiation since it was chopped while the radiation resulting from sample heating was not.

The radiometer used to measure the reflected radiation comprised a 28.6mm diameter Irtran II meniscus type lens with a 25.4mm focal length to focus the reflected radiation through a narrow-band spike filter, with peak transmission at 10.6 μ m, onto a 0.5 by 0.5mm thermistor bolometer infrared detector. The radiometer was located 37.5cm from the surface of the samples and moved by the goniometer in a path equidistant from the object plane over an angular range of 30 to 120 degrees with respect to the optical axis of the laser.

The electrical signals from the laser power meter and radiometer were amplified and recorded on an oscillographic recorder. A schematic diagram of this system is shown in figure 3.

The laser output power was monitored periodically during the reflectivity measurements. A glass-bead-blasted flat aluminum plate was used to approximate a perfect diffuse standard reflector. The reflectivity of this plate was assumed to be 0.80.^{4,5} The radiation reflected from the standard

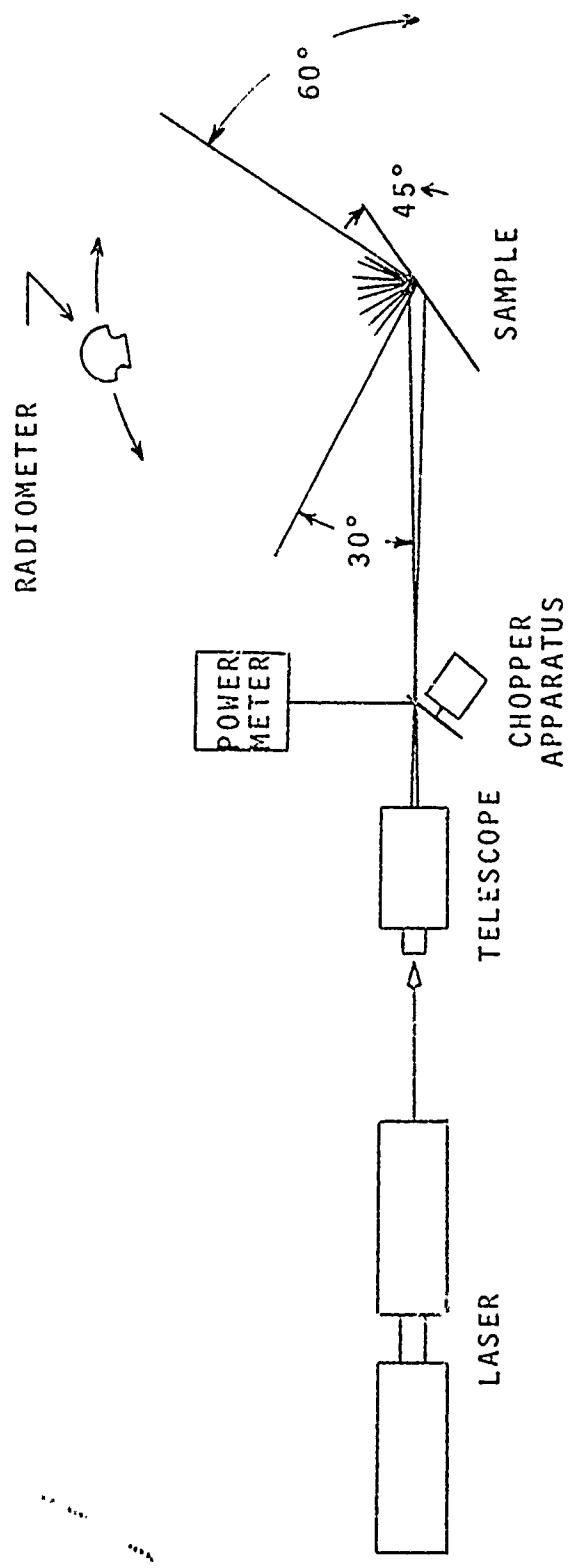


FIGURE 3 SCHEMATIC DIAGRAM OF THE EQUIPMENT
 USED TO DETERMINE REFLECTIVITIES

sample was measured at 0, 15, 30, 45, 60, and 75 degrees with respect to the normal to the sample before each sample run, and the outputs were recorded. The sample of interest was then mounted on the sample holder, and the laser and recorder were operated. The radiation reflected from the sample was also recorded over the angular range from 0 to 75 degrees (with respect to the sample normal) in 15-degree increments.

Once the detector outputs corresponding to the standard and the sample are recorded on oscilloscope paper, the outputs are compared. The peak-to-peak amplitude of the signal recorded at each angle was measured, and the measured displacements were used to determine the reflectivity.

The total spectral reflectivity $r(\lambda)$ at the wavelength λ is defined as

$$r(\lambda) = \frac{1}{I_0(\lambda)} \int I(\theta, \phi, \lambda) d\phi \sin \theta d\theta \quad (6)$$

where $I_0(\lambda)$ is the total incident flux at wavelength λ and $I(\theta, \phi, \lambda)$ is the reflected flux density in the direction specified by the variables θ and ϕ . The integral above is performed over the surface of a hemisphere above the specimen. Time did not permit the collection of data for all angles θ and ϕ within this hemisphere. Therefore, $I(\theta, \phi, \lambda)$ was assumed to have no explicit dependence on ϕ ; thus the integral given above was replaced by

$$r(\lambda) = \frac{2}{I_0(\lambda)} \int I(\theta, \lambda) \sin \theta d\theta \quad (7)$$

For convenience, total reflectivity measurements were obtained relative to the total reflectivity of a standard sample. Thus,

$$r(\lambda) = r_s(\lambda) \frac{\int d\theta \sin \theta I(\theta)}{\int d\theta' \sin \theta' I_s(\theta')} \quad (8)$$

where the subscript s refers to the standard sample. The integrals are evaluated numerically by simple stepwise approximation.

RESULTS AND DISCUSSION

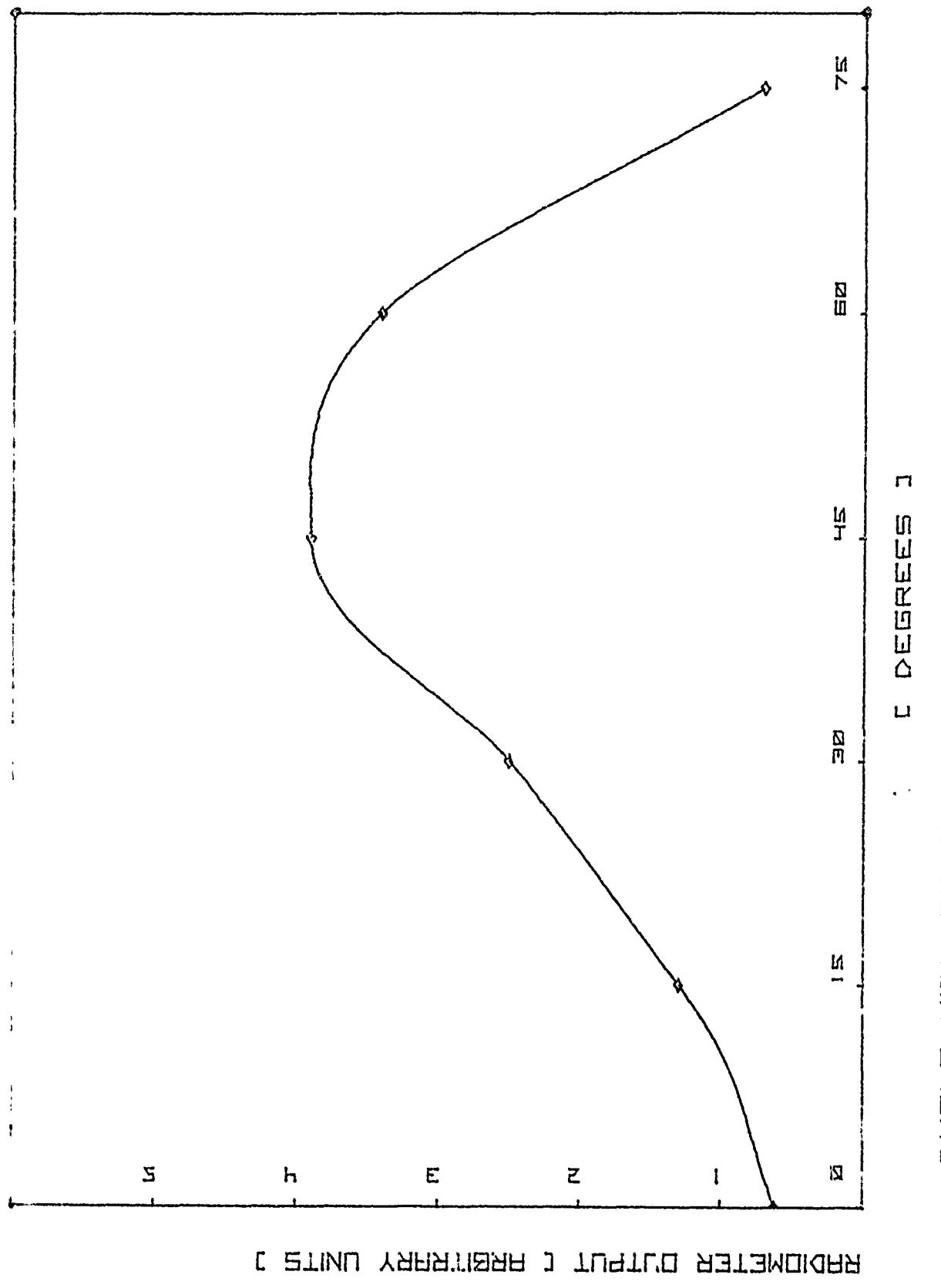
Several environmental and military samples were tested: rubber sheet, cement, asphalt, rock, firebrick, asbestos sheet, plate glass, walnut veneer, rough pine, painted steel, rusted steel, manganese-phosphate-coated barrel section, grass, leaves, earth, and sand. Each sample was tested in the same manner, as previously described, with the radiation reflected from the standard measured before testing each sample.

The standard sample comprised a 3 by 5 by 1/4-inch aluminum sheet that had been glass-bead blasted to try to obtain a diffuse reflecting surface with a reflectivity of 0.80. A plot of the radiometer output as a function of the angle of the radiometer with respect to the normal to the sample is shown in Figure 4. Note the peaking about the specular reflection angle, viz. 45 degrees (with respect to the normal to the sample). The intensity variation about this angle resembles a cosine distribution.

A 6 by 6 by 0.0625-inch rubber pad was the first sample tested, and posed a peculiar problem. This problem arose when, during the course of the test, the laser radiation heated the rubber enough to expand the material so that a bubble occurred on the surface. This bubble caused the reflected radiation to vary rapidly while all the other parameters remained fixed. Turning off the laser and allowing the rubber to cool between readings was required to alleviate this problem. The use of this method resulted in reliable data being obtained. The total reflectivity of the rubber sample was 0.066 as calculated from the data in Table I. A typical graph of the radiometer output voltages as a function of the angle for the rubber pad test is shown in Figure 5. This graph and the corresponding graph for the standard (Figure 4) have similar shapes, which indicate that the specular reflection is comparable in both instances.

The second sample tested was an irregularly shaped piece of flat concrete roadway material. This sample was positioned such that the flat surface was in the same plane as the surface of the standard sample when it was tested. The reflectivity values determined for this sample are shown in Table II, with the total reflectivity being 0.024.

The third sample tested was an irregularly shaped piece of asphalt roadway material with small white rock fragments intermixed throughout the sample. This sample was first positioned



ANGLE WITH RESPECT TO THE NORMAL TO THE SAMPLE

RADIOMETER OUTPUT VERSUS ANGLE FOR THE
BEAD BLASTED ALUMINUM STANDARD SAMPLE

FIGURE 4

TABLE I
RADIOMETER OUTPUT IN ARBITRARY UNITS

<u>Angle*</u>	<u>Bead Blasted Aluminum</u>	<u>Rubber Sheet</u>
0°	0.80	0.10
15°	1.95	0.13
30°	3.78	0.33
45°	6.45	0.86
60°	6.23	0.48
75°	1.90	0.29
$r(\lambda = 10.6)**$		0.066

* With respect to the normal to the sample surface.

** Total reflectivity

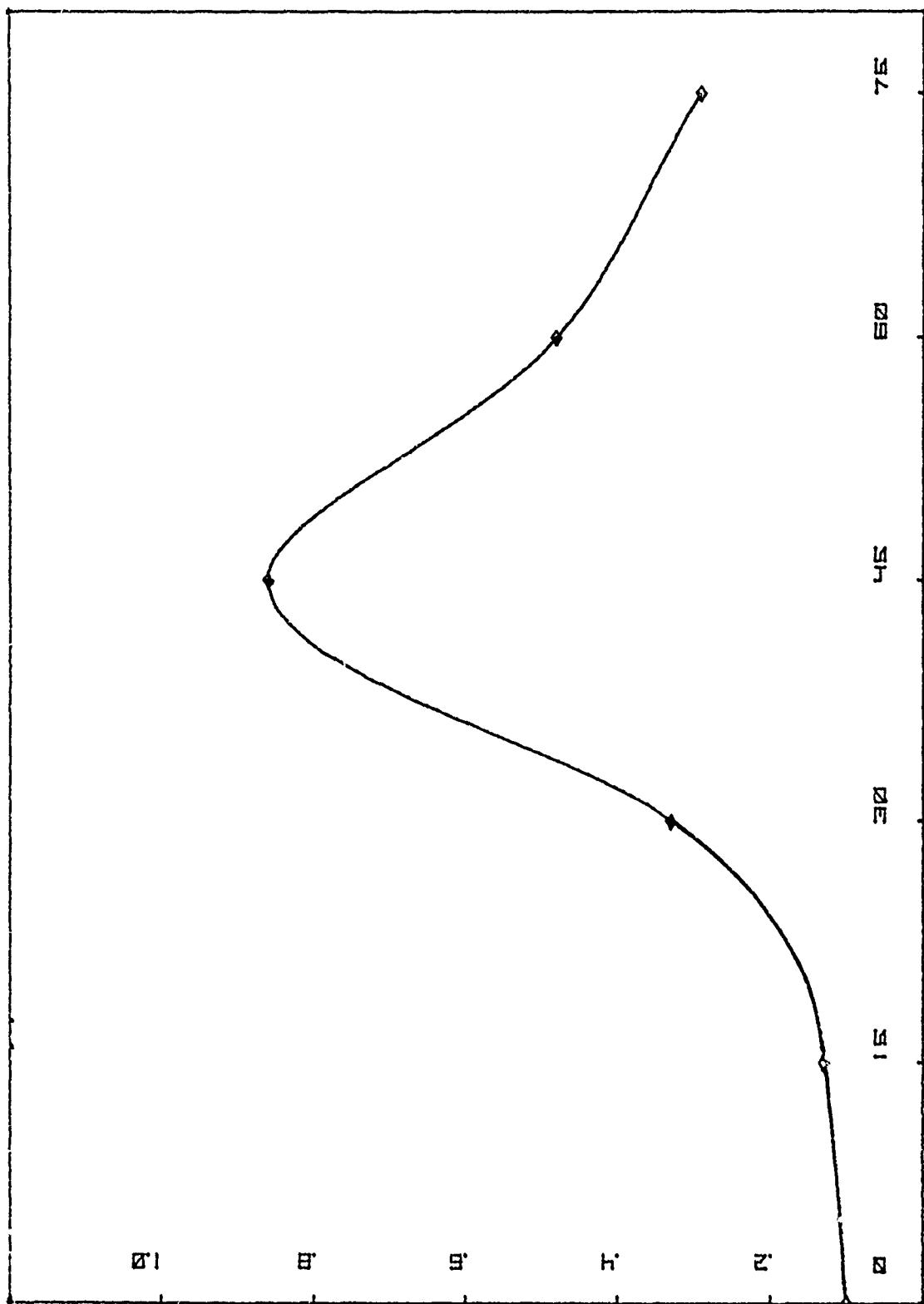


FIGURE 5

RADIOMETER OUTPUT VERSUS ANGLE FOR
THE RUBBER SAMPLE

ANGLE WITH RESPECT TO THE NORMAL TO THE SAMPLE
[DEGREES]

RADIOMETER OUTPUT [ARBITRARY UNITS]

TABLE II

RADIOMETER OUTPUT, IN ARBITRARY UNITS

<u>Angle</u>	<u>Bead Blasted Aluminum</u>	<u>Concrete Roadway Material</u>	<u>Asphalt White Rocks Up</u>	<u>Asphalt White Rocks Down</u>
0°	1.60	0.25	0.3	0.22
15°	2.88	0.20	0.25	0.20
30°	5.38	0.20	0.22	0.20
45°	10.55	0.30	0.17	0.15
60°	8.3	0.32	0.15	0.10
75°	6.82	0.10	0.10	0.10
Total Reflectivity:		0.024	0.017	0.014

on the goniometer sample holder with the flat road surface upward; almost all of the surface was covered by small white rock fragments which are typical of this type of paving material. The total emissivity of this surface was determined to be .017; the particular values are shown in the table.

The effect of the surface rock fragments on the reflectivity readings was also determined by inversion of the asphalt sample. On this side of the sample, the rock fragments were present but were still covered by a thin coating of the black asphalt material. In addition, this surface had more surface irregularities than the other with assorted 0.25-inch pits and crevices approximately 0.25-inch across. This side had a total reflectivity of 0.014; the reading at each angle is presented in Table II. Therefore, the presence of the rock fragments on the surface has negligible influence on the reflectivity of the asphalt sample.

In the fifth test, a white rock resembling limestone was utilized as a target. The first side tested was relatively flat, lengthwise; however, it was curved slightly in the other direction. This rock was placed on the sample holder with the longest dimension vertical to minimize effects due to the curvature of the surface. The total reflectivity of this surface was determined to be 0.043 from the data in Table III.

During the sixth test, the limestone rock previously described was inverted. This inverted side had an offset ridge that extended lengthwise with each side sloping gently away from the center. The sample was mounted with random orientations in the path of the laser beam. The resulting reflectivity values of this sample are shown in Table III; the total reflectivity value was 0.044. As was the case with the asphalt sample, very little difference in the reflectivity values was observed when the rock was turned over. This can be explained by the fact that the radiometer was focused on a spot on the sample; therefore, the orientation of the surface was unimportant.

A 3 by 4.5 by 1-inch firebrick was used in the seventh test. The firebrick was flat and had a white porous surface. This surface had an total reflectivity of 0.010; the individual readings are shown in Table III.

For the eighth test, a 4 by 4-inch sheet of asbestos was used as a target for the laser radiation. This sheet which

TABLE III
RADIOMETER OUTPUT, IN ARBITRARY UNITS

<u>Angle</u>	<u>Bead Plastered Aluminum</u>	<u>Limestone (Flat Side Up)</u>	<u>Limestone (Flat Side Down)</u>	<u>Firebrick</u>	<u>Asbestos</u>	<u>Plate Glass</u>	<u>Walnut Hardwood</u>	<u>Pine Softwood</u>	<u>Olive Drab Paint On Steel</u>	<u>Steel Plate (Rusted)</u>
0°	0.62	0.16	0.15	0.09	0.13	0	0.14	0.09	0.04	0.06
15°	1.3	0.17	0.16	0.06	0.24	0	0.19	0.10	0.04	0.08
30°	2.5	0.14	0.16	0.04	0.48	0	0.31	0.14	0.06	0.13
45°	3.9	0.16	0.14	0.03	0.52	0.09	0.19	0.16	1.29	0.12
60°	3.4	0.14	0.14	0.02	0.35	0	0.39	0.06	0.37	0.16
75°	.71	0.03	0.10	0.02	0.16	0	0.24	0.04	0.04	0.10
Total reflectivity:	0.043	0.044	0.010	0.113	0.006	0.091	0.030	0.131	0.041	

was smooth had an average reflectivity of 0.113; the individual values for this sample are shown in Table III.

A 6 by 6 by 0.5-inch piece of plate glass was used in the ninth test. As would be expected, the glass sample was extremely smooth and flat. This sample proved to be a very good absorber of $10.6\mu\text{m}$ radiation since the reflected radiation was detectable only at 45 degrees. The total reflectivity of the plate glass surface was consequently determined to be 0.006.

In the next test, the reflectivity of a 6 by 6 by 0.04-inch piece of planed unsanded walnut hardwood was measured. The surface of the walnut was flat and smooth, but not glossy. This sample was mounted, as previously described, and the total reflectivity value was determined to be 0.091 from the data shown in Table III.

For the eleventh test, a 6 by 6 by 0.5-inch flat piece of rough, unsurfaced, pine softwood was utilized. This sample had a total reflectivity of 0.030, which is significantly different from the value found for the walnut hardwood sample.

A 8 by 8 by 0.25-inch flat steel plate was used in the performance of the twelfth and thirteenth tests. This plate was divided into two equal sections, one section was painted with olive drab lacquer and the other section was left uncoated. The plate was then placed outdoors for 6 months (from June to December) to allow the surface to weather naturally. During the weathering process, the paint lost the glossy appearance it originally had, while the unpainted surface rusted. The total reflectivity value determined from the painted sample was 0.131, and that value determined from the oxidized half of the sample was 0.041. The data used to determine these values is shown in Table III.

For the fourteenth test, a sand surface was to be tested. However, since the sand was in a loose form, the surface did not remain parallel to the desired 45-degree angle of the sample holder. Therefore, the sand had to be affixed to a rigid surface to permit the measurements to be made. A thin coating of a nitrocellulose type glue was applied to an aluminum sheet and the sand was spread over the glue-covered surface. After the glue dried, the excess sand was removed and a flat surface of sand remained. This sample was mounted on the sample holder in the same manner as the other specimens tested; the resulting total reflectivity value was 0.035; and the data is shown in Table IV.

A clump of randomly-oriented blades of tall growing grass was the fifteenth sample tested. This sample was mounted so that the approximate midpoint of the growth was located at the center of the arc traversed by the radiometer, with the laser radiation incident on this central area. The resulting average reflectivity value from the grass sample was determined to be 0.017.

After the grass sample was tested, the soil from which the grass was growing also was tested. The grass was cut short and the soil was then positioned on the sample holder, with the grass inverted. Only the bare soil remained exposed to the laser radiation. The total reflectivity of soil was determined to be 0.017.

For the seventeenth test, leaves from a maple tree were utilized as a target for the $10.6\mu\text{m}$ radiation. A single leaf was laid flat on the sample holder and the measurements taken. The resulting total $10.6\mu\text{m}$ reflectivity was determined to be 0.028. The individual readings are shown in Table IV.

For infrared temperature-measurement applications, the reflectivity measurements of a manganese-phosphate-coated 20mm barrel section were of interest. During an FY70 investigation conducted in the Research Directorate, the emissivity of the same barrel section was determined.¹ In this work, a hole was drilled in the side of the barrel section. This hole permitted an infrared radiometer to be focused into the interior of the barrel, which served as a very good approximation to a black-body cavity with a minimum theoretical emissivity of 0.995.⁶ At any given temperature, the radiation emitted by the barrel interior and the radiation emitted by the exterior surfaces could be measured by means of the infrared radiometer. The ratio of the radiation intensities, at equilibrium temperature, is the emissivity of the exterior surface.

Because heating of the barrel was required for these measurements the barrel was modified in the following manner a thick layer of asbestos was wrapped around the barrel followed by a layer of nickel-chromium resistance wire, and covered by still another layer of asbestos. Heating was accomplished by an AC voltage applied to the resistance wire. A circumferential slot was made in the asbestos sheath to expose the hole and the surface for emissivity measurements.

Iron-constantan thermocouples were placed on the interior and the exterior of the barrel section to continuously monitor

TABLE IV

RADIOMETER OUTPUT, IN ARBITRARY UNITS

<u>Angle</u>	<u>Bead Blasted Aluminum</u>	<u>Coarse Sand</u>	<u>Grass</u>	<u>Soil</u>	<u>Maple Leaves</u>
0°	0.57	0.09	0.04	0.06	0.10
15°	1.24	0.08	0.04	0.06	0.11
30°	2.18	0.07	0.05	0.05	0.14
45°	3.47	0.09	0.04	0.04	0.08
60°	3.20	0.09	0.06	0.05	0.08
75°	0.97	0.13	0.05	0.05	0.04
Total Reflectivity:		.035	0.017	0.017	0.028

the temperature and to ensure that an equilibrium condition had been achieved. The intensity of the emitted radiation was measured with an infrared radiometer that was first focused onto the surface and then into the black-body cavity. The average emissivity for the manganese-phosphate-coated barrel section, by this method, was 0.92 corresponding to average reflectivity of 0.08.

The CO_2 laser reflectivity measurement technique was utilized to test the same manganese-phosphate-coated barrel section. The barrel was mounted on the sample holder with the axis of the barrel parallel to the 45 degree sample holder. The laser and the radiometer were operated in the same manner as before. The total reflectivity of the manganese-phosphate-coated barrel section, by the CO_2 laser technique, was determined to be 0.048, from the data in Table V. The close agreement of the barrel reflectivity with that determined by previous techniques developed during FY70 lends confidence to this laser technique.

CONCLUSIONS

The feasibility of using a laser system for the non-destructive determination of emissivities of Army material and measurement of the reflectivities of target and environmental surfaces at 10.6 micrometers (μm) with pulsed CO_2 laser radiation was positively established in the Research Directorate of the Weapons Laboratory at Rock Island. The use of this technique has significantly improved procedures for determining the emissivity of Army material since measurements can be performed in less time and without the destruction of the component. In addition, this information will be invaluable for determining the advisability of using a TEA CO_2 laser for target designator applications and for the use of deliberate off-target designation in conjunction with a bifunctional seeker for guided projectile applications.

A word of caution is appropriate regarding the values quoted for the total reflectivities. In the derivation of Equation 8, which was used to obtain the total reflectivities, one assumed that the radiation would be symmetric about the normal to the surface and have no ϕ dependence (azimuthal symmetry). An examination of Figures 4 and 5 does not support this view. One could alternatively assume azimuthal symmetry about the specular reflection direction. Integrals performed in this manner gave results that varied from very nearly the values quoted in this document to somewhat larger. The occurrence of integrals as a ratio in Equation 8 and the similarity of the shapes of the reflectance curves would tend to cancel the

TABLE V
RADIOMETER OUTPUT, IN ARBITRARY UNITS

<u>Angle</u>	<u>Bead Blasted Aluminum</u>	<u>Manganese Phosphate Coated 20mm Barrel Section</u>
0°	0.99	0.07
15°	1.22	0.08
30°	1.10	0.09
45°	2.12	0.10
60°	0.57	0.07
75°	0.57	0.07
Total Reflectivity: 0.048		

error introduced by invalid assumptions regarding reflection symmetry and probably accounted for the agreement of the values for total reflectivity quoted here and those obtained by other algorithms. It is clear, however, that precise knowledge of the reflectivity behavior of common materials at $10.6\mu\text{m}$ requires measurement at values of the spherical angles θ and ϕ effectively covering a hemisphere over the sample and for various orientations of the incident beam

RECOMMENDATIONS

Research should be continued to determine the advisability of using a TEA CO₂ laser as a target designator for CLGP applications. This work should include the in house construction of a TEA laser, experimentation with various electrode configurations, and the testing of closed- and open-cycle gas systems. In addition, reflectivity measurements should be performed on a representative sample of specimens to determine if high-power (approximately 200,000 watts) and short-duration (175 nanoseconds) pulses have any effect on the reflectivity characteristics of the samples tested. Calibration of the standard by direct comparison of the reflected radiation and the incident beam is desirable. This can be accomplished by use of a second radiometer in place of the power meter. Precise neutral density filters will be required to attenuate the directly viewed laser radiation to prevent damage to the detector. Finally, reflectivity measurements should be made over the entire hemisphere over each sample and for various orientations of the incident laser beam

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